

Brightness Oscillations in Models of Young Binary Systems with Low-Mass Secondary Components

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Abstract

We consider a model for the cyclic brightness variations of a young star with a low-mass companion that accretes matter from the remnants of a protostellar cloud. At small inclinations of the binary orbit to the line of sight, the streams of matter and the density waves excited in the circumbinary disk can screen the primary component of the binary from the observer. To study these phenomena, we have computed grids of hydrodynamic models for binary systems by the SPH method based on which we have constructed the phase light curves as a function of the rotation angle of the apsidal line relative to the observer. The model parameters were varied within the following ranges: the component mass ratio $q = 0.01 - 0.1$ and the eccentricity $e = 0 - 0.5$. We adopted optical grain characteristics typical of circumstellar dust. Our computations have shown that the brightness oscillations with orbital phase can have a complex structure. The amplitudes and shapes of the light curves depend strongly on the inclination of the binary orbit and its orientation relative to the observer and on the accretion rate. The results of our computations are used to analyze the cyclic activity of UX Ori stars.

Key words: *young binary systems, hydrodynamics, cyclic activity, accretion.*

1 INTRODUCTION

In this paper, we continue our numerical simulations of the cyclic circumstellar extinction variations in young binary systems accreting matter from the remains of a protostellar clouds begun in our previous works (Sotnikova and Grinin 2007; Demidova et al. 2010). The goal of these computations is to ascertain what photometric effects may be expected when the binary orbit is inclined at a small angle to the line of sight. Sotnikova and Grinin (2007) showed that three harmonics could be observed in the circumstellar extinction variations in such binaries as a result of periodic gravitational perturbations produced by the orbital motion of the components. The shortest of them has a period equal to the orbital one and is produced by the streams of matter that periodically appear at the inner boundary of the circumbinary disk and penetrate into its central region. The other two, longer periods are attributable to the precession of the circumbinary disk and the motion of a one armed density wave in it. All three harmonics can be observed simultaneously only in the presence of sufficiently strong perturbations. Such conditions can take place in binary systems whose components do not differ greatly in mass (this case was considered by Demidova et al. (2010)). In this paper, we consider binary systems with low-mass secondary components in which only one mode of extinction oscillations with a period equal to the orbital one is realized. We use a binary model that consists of a primary component with mass M_1 and a secondary component with mass M_2 . The binary is embedded in a circumbinary gas-dust disk whose matter is accreted onto the binary components (Fig. 1). The disk is assumed to be coplanar with the orbit. The extreme case of such a binary is a young star with a protoplanetary disk and a giant planet at the phase of intense accretion. The input parameters of the problem are the accretion rate onto the binary components (\dot{M}_a), the component mass ratio $q = M_2/M_1$, the orbital inclination to the line of sight θ , the eccentricity e , the rotation angle of the apsidal line relative to the observer ϕ , and the parameter c characterizing viscosity. The goal of this paper is to compute the light curves of such binaries and to study their dependence on model parameters.

2 THE COMPUTATIONAL METHOD

As in our previous papers, we consider a binary system that accretes matter from a circumbinary (CB) disk coplanar with the orbital plane. The hydrodynamic models of such a binary were computed by the SPH (Smoothed Particle Hydrodynamics) method described in detail by Sotnikova (1996). For each model, we computed the column density of test particles toward the primary component of the binary as a function of time expressed in units of the orbital period. As a rule, the computations were performed for several hundred periods.

The area of the section of the column s along which the particle column density in the chosen direction was determined was specified as $s = 2h \times 2h$. In our implementation of the method, the smoothing length was assumed to be constant and was specified in fractions of the semimajor axis of the binary orbit, $h = 0.1a$. At each point, this provided at least 30 neighboring points over which the hydrodynamic quantities were averaged. Our computations showed this value of s to be optimal for the solution of the formulated problem (at lower values of s , the influence of fluctuations is enhanced; at higher values, the time resolution of the calculated characteristics deteriorates).

Our quantitative analysis of the computational results began with the removal of the trend in the variations of the test particle column density attributable to the decrease in their number in the binary system because of accretion onto its components. The trend

was modeled by a fifth-degree polynomial. Our computations showed that this provided a satisfactory removal of the trend for all of the models considered. Subsequently, we passed from the column density of test particles $n(t)$ to the column density of real dust grains $n_d(t)$ (for more detail, see Demidova et al. 2010). To reduce the influence of random fluctuations when the phase dependences of n were computed, the current values of $n(t)$ were folded with the orbital period for a time interval of 50 binary revolutions.

One of the key parameters of the computed models is the specified accretion rate onto the binary components \dot{M}_a . This parameter was compared with the accretion rate of test particles obtained during the computations (for more detail, see Sotnikova and Grinin 2007). The mass of a single test particle was determined as follows: $m_d = P \cdot \dot{M}_a / N$. Here, P is the orbital period and N is the total number of test particles accreting onto both components in one binary revolution. Below, in our computations, we took \dot{M}_a to be $10^{-9} M_\odot/\text{yr}$. As our computations showed, this value of the accretion rate is high enough to produce a strong modulation in the brightness of the primary component.

Having calculated the mass of a single test particle by the method described above, we obtain the matter column density in g/cm^2 . To determine the optical depth of the dust on the line of sight, we should specify the opacity κ per gram of matter. This parameter depends on the type and sizes of the dust grains and on the dust-to-gas ratio. As in our previous papers, below we adopted an average (for the interstellar medium) dust-to-gas ratio of 1 : 100 and $\kappa = 250 \text{ cm}^2/g$ typical of circumstellar extinction in Johnson's B photometric band (Natta and Whitney 2000)¹. Multiplying the matter column densities calculated in this way by κ , we will obtain the optical depths τ for each instant of time.

The intensity of the radiation from young stars is known to consist of two components: the intensity of the direct stellar radiation I_* (in our case, the primary component of the binary) attenuated by a factor of $e^{-\tau}$ and the intensity of the radiation scattered by circumstellar dust I_{sc} :

$$I_{obs} = I_* e^{-\tau} + I_{sc}, \quad (1)$$

The contribution of the scattered light to the total radiation typically does not exceed a few percent. Therefore, below, when studying the pattern of variability in the primary component of the binary, we took the intensity of the scattered radiation in (1) to be zero. The light variations of the primary component are expressed in magnitudes: $\Delta m = -2.5 \cdot \log I_{obs}$ (I_* is taken as unity). Hence it follows that $\Delta m \sim \tau$, and since τ is proportional to \dot{M}_a ,

$$\Delta m \sim \dot{M}_a \quad (2)$$

This relation allows the light curves computed for one value of \dot{M}_a to be recalculated for other values of this parameter.

3 MODEL LIGHT CURVES

We computed theoretical light curves for binary systems by the method described above. The basic model parameters are listed in the table. In all models, the mass of the primary

¹It should be noted that these circumstellar dust parameters correspond to early evolutionary stages of protoplanetary disks. In the process of coagulation, the dust grains become larger and settle toward the disk plane. However, as observations show, the small dust grains that make a major contribution to the opacity of matter are retained in the protoplanetary disks for a long time, of the order of several Myr. As the calculations by Birnstiel et al. (2009) show, this is because the efficiency the process opposite to coagulation, the destruction of particles in collisions, is high.

component is $2M_{\odot}$, i.e., a value typical of UX Ori stars (Rostopchina 1999); c is the dimensionless speed of sound in the matter expressed in units of the orbital velocity of the secondary component at $e = 0$. The parameter c enters into the expression for the disk viscosity. Note that the values of c used in our hydrodynamic computations correspond to a matter temperature of the order of several hundred kelvins. The number of test particles N used in our SPH simulations is 60 000 and the smoothing length is $h = 0.1a$. As in Demidova et al. (2010), the orbital period is taken to be five years.

The model parameters were varied within the following ranges: the component mass ratio $q = M_2/M_1 = 0.01 - 0.1$ and the eccentricity $e = 0 - 0.5$; the dimensionless speed of sound in the CB disk c was taken to be 0.05 ("warm" disk) for all of the models except model 5. For this model, $c = 0.02$ ("cold" disk). Our computations were performed for several inclinations of the binary orbit to the line of sight and four rotation angles of the apsidal line relative to the observer: 0° , 90° , 180° , and 270° . In the frame of reference adopted here, the angle $\phi = 0$ corresponds to the case where the apastron lies between the primary component and the observer. The angles were counted off in the direction of rotation of the binary. The choice of inclination (from 0° to 12°) was restricted by the finite number of test particles used in our computations and by the necessity of avoiding great statistical fluctuations in the particle column density at larger angles θ . As was said above, to suppress the fluctuations, the current values of $n(t)$ for the chosen phase intervals were summed over 50 revolutions and were then averaged and smoothed. As an example, Fig. 2 shows the light curve computed in this way along with the "cloud" of points from which it was obtained.

Figures 3-6 present the light curves of a binary system in models with eccentric orbits for two indications of the disk plane to the line of sight and several rotation angles of the apsidal line relative to the observer. We see that the light curves depend significantly not only on the orbital inclination to the line of sight but also on the orientation of the apsidal line relative to the observer. Both the amplitude and the shape of the light curves change with these parameters.

The dependence of the light-curve shape on the orbital inclination to the line of sight is quite understandable if we take into account the fact that the extinction variations with orbital phase are caused partly by the streams of matter propagating from the CB disk to the central part of the binary system and partly by the CB disk matter falling on the line of sight as it rotates. The strong influence of the orientation of the apsidal line relative to the observer on the light curves in models with eccentric orbits is caused by an azimuthal asymmetry of the inner CB disk gap with a nearly elliptical shape.

In model 1 (Fig. 3) with the component mass ratio $q = 0.1$ and eccentricity $e = 0.3$ at a given accretion rate, an appreciable variability amplitude is observed for all four orientations of the binary orbit relative to the observer. At rotation angles of the apsidal line relative to the observer of 0° and 180° , the amplitudes for inclinations of 0° and $7^\circ.5$ are comparable, because the size of the column section is finite: at such sizes, the number of test particles in the column was found to be close in order of magnitude at a difference in angles of $7^\circ.5$.

In model 2 (Fig. 4), we considered inclinations of 0° and 12° . For the inclination of 0° , the minimum variability amplitude was obtained for rotation angles of the apsidal line of 0° and 90° , while for the inclination of 12° the amplitude is at a minimum for 180° and 270° . This suggests that the CB disk is azimuthally very inhomogeneous even when the secondary component is a factor of 10 less massive than the primary component. It is this inhomogeneity that is reflected in the behavior of the particle column density.

In models 3 and 4 (Figs. 5 and 6), we adopted the minimum masses of the secondary component we considered, $q = 0.03$ and $q = 0.01$. The variability amplitude for an inclination of 0 is $2-3^m$; for inclinations of 9° and 10° , it is about $0^m.8$. Thus, the noticeable photometric

variability of the star may be due to the orbital motion of a brown dwarf or a giant planet. For model 4 (with a circular orbit), the result of our computations does not depend on the orientation of the binary orbit.

In model 5 (with the lowest viscosity), the disk is too thin and dense. As a result, when observed edge on, the radiation from the primary component is completely screened by the disk, while for an inclination of 5° the number of particles on the line of sight does not exceed the fluctuation level.

The above-listed results were obtained without allowance for the influence of scattered radiation. Nevertheless, they are also valid in real systems with a noticeable contribution from scattered light. This can be seen from Fig. 7, which shows two light curves. One of them was computed for $I_{sc} = 0$ and the other was computed for $I_{sc} = 0.1I_*$. We see that the scattered radiation reduces the amplitude of the light variations, but their overall appearance is retained.

It should be noted that to obtain statistically significant results in counting the number of test particles on the line of sight, we had to restrict ourselves to a small range of orbital inclinations to the line of sight ($\leq 12^\circ$). To reduce the influence of fluctuations in SPH models, it is necessary to use a larger number of particles, which requires much computational time. Test computations showed that in such models an appreciable brightness modulation amplitude could also be obtained at larger inclinations of the binary orbit to the line of sight (especially in the models with a "warm" and "hot" CB disk), but this requires higher accretion rates. Note that the accretion rate adopted in our computations ($10^{-9}M_\odot$) is the lower limit of \dot{M}_a for young stars. The accretion rate onto Herbig Ae/Be stars is known (see, e.g., Garcia Lopez et al. 2006) to reach $10^{-6}M_\odot$. This means that, in our case, there is a large margin (about three orders of magnitude) for increasing this parameter.

4 DISCUSSION AND CONCLUSION

The above results are quite expectable, because it is clear from general considerations that something must vary with a period equal to the orbital one in young binary systems that accrete matter from the remnants of a protostellar cloud. The unexpected and nontrivial result of our computations is the conclusion that the source of perturbations capable of generating a photometric wave with an appreciable amplitude in the behavior of the brightness of a young star could be a companion that is a factor of 100 less massive than the star itself. This means that a brown dwarf or a giant planet can be such a companion. Therefore, studying the cyclic activity of young stars can contribute to the discovery and study of such objects.

Our computations showed that an accretion rate onto the binary components of $10^{-9} M_\odot$ is quite sufficient to produce a strong modulation in the brightness of the primary component at the orbital inclinations for which the computations were performed. It means that at a "favorable" (nearly edge on) disk orientation, the cyclic activity caused by extinction variations can be observed even in young objects with weak evidence of accretion. An example of such an object is the WTTS star (weak-line T Tauri star) V718 Per, in which shallow eclipses with a period of 4.7 yr and a duration of 3.5 yr are observed (see, e.g., Grinin et al. 2008).

The accretion rate onto UX Ori stars to be discussed below is approximately an order of magnitude higher (Tambovtseva et al. 2001; Muzerolle et al. 2004). This means that the cyclic activity of such stars caused by periodic extinction variations can be observed at larger inclinations of the circumstellar disks to the line of sight. In models with eccentric

orbits, the amplitude and shape of the phase light curves depend not only on the inclination of the binary orbit to the line of sight but also on its orientation in space; as was noted above, this is attributable to the elliptical shape of the inner gap and can be observed even in binaries with a low-mass secondary companion. At certain orbital inclinations, both the CB disk matter and the streams of matter penetrating into the inner regions of the binary are involved in producing variable extinction on the line of sight. In such cases, the light curves can have a fairly complex shape (see, e.g., Fig. 5).

Sotnikova and Grinin (2007) and Demidova et al. (2010) pointed out the possible connection of the cyclic activity of UX Ori stars with the extinction variations due to the presence of perturbing bodies (protoplanets, brown dwarfs, components of binary systems) in their neighborhoods. Observations show that the duration of the photometric cycles ranges from several months (Artemenko et al. 2010) to ten or more years (see, e.g., Shakhovskoi et al., 2005). Their amplitudes range from a few tenths of a magnitude to two magnitudes in the V band, i.e., they are comparable to the theoretical values.

As an example, Figure 8 shows the phase light curve of the star CO Ori (Rostopchina et al. 2007), which is a long series of photometric observations of this star folded with a period of 12.4 yr. The behavior of the linear polarization in this star (observed synchronously with photometry) strongly suggests that periodic circumstellar extinction variations are responsible for the cyclic variations in its brightness. We see from Fig. 8 that the cyclic brightness variations in CO Ori are generally similar in shape to the model light curve presented in Fig. 2. It should be noted that similar (in shape) light curves can also be obtained in models with noticeably differing parameters. Therefore, the shapes of the observed activity cycles and their amplitudes cannot be used, for example, to estimate the mass of the secondary component mass.

In conclusion, it should be noted that the accretion disk of the primary component, if it contains dust, can also be the source of photometric activity of a young binary system. This requires that the disk radius be larger than the radius of the dust sublimation zone. For Herbig Ae stars, to which most of the UX Ori stars belong, the radius of this zone is 0.5 AU. Therefore, at a disk radius of the order of several AU, the existence of circumstellar extinction and its possible variations should be taken into account when the light curves of young binary systems are analyzed.

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Table 1: Model parameters

Model	e	q	c
1	0.3	0.1	0.05
2	0.5	0.1	0.05
3	0.5	0.03	0.05
4	0.0	0.01	0.05
5	0.5	0.1	0.02

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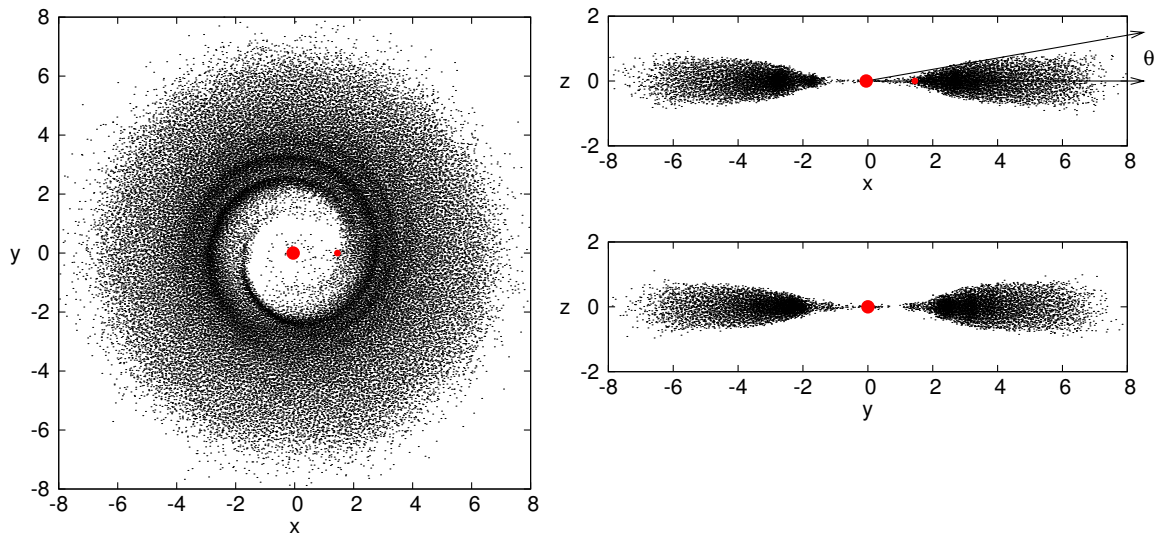


Figure 1: Distribution of matter in the binary model 3 ($e = 0.5$, $q = 0.03$): (a) top view; (b) and (c) disk sections in the xz and yz planes. The scale along all three axes is given in units of the orbital semimajor axis.

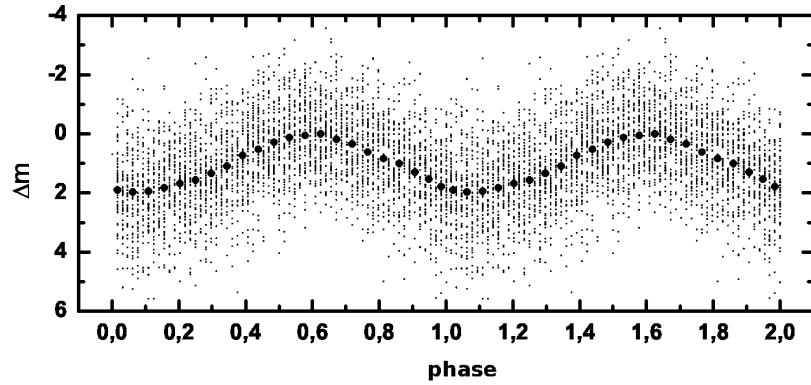


Figure 2: Phase light curve for model 1; the inclination of the binary orbit to the line of sight is $\theta = 7^\circ.5$, the rotation angle of the apsidal line is 180° . The dots indicate the nonaveraged values of Δm ; the circles indicates the averaged and smoothed values.

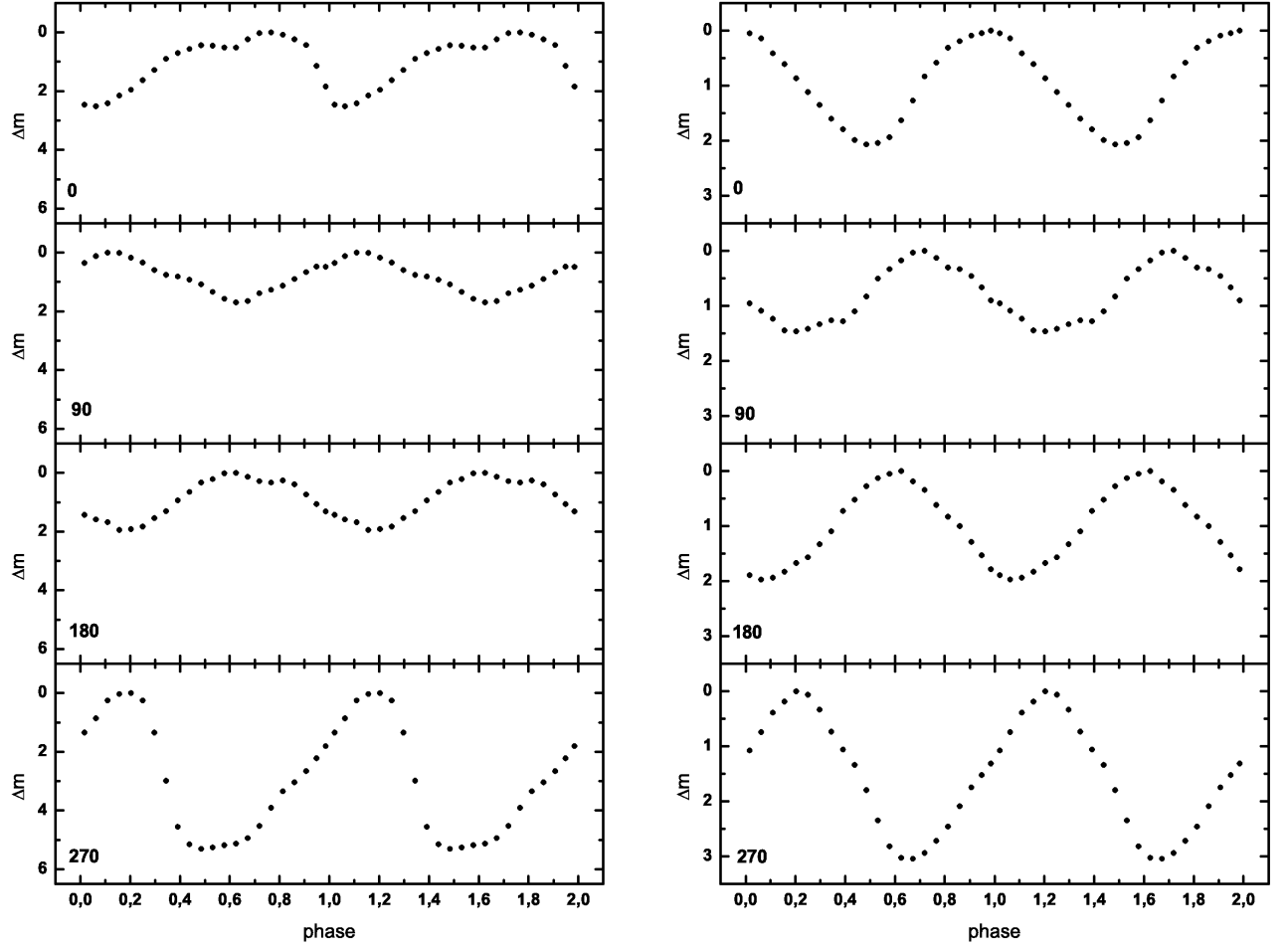


Figure 3: Phase light curves in model 1 ($e = 0.3$, $q = 0.1$): (a) the line of sight lies in the orbital plane, (b) the disk is inclined at an angle of $7^\circ.5$ to the line of sight. The rotation angle of the apsidal line relative to the observer is indicated in the lower left corner of each diagram.

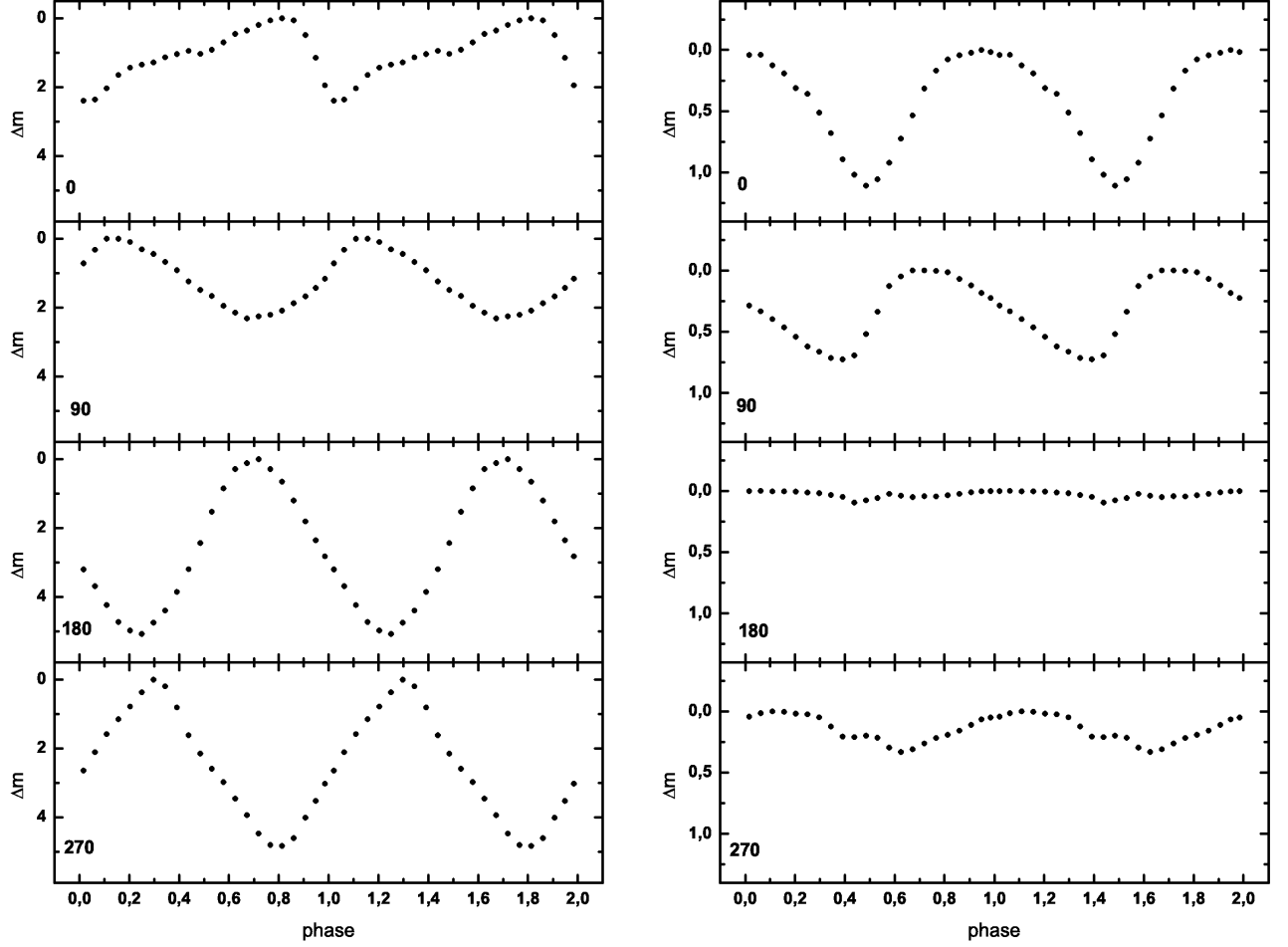


Figure 4: Same as Fig. 3 for model 2 ($e = 0.5$, $q = 0.1$); (b) the binary orbit is inclined at an angle of 12° to the line of sight.

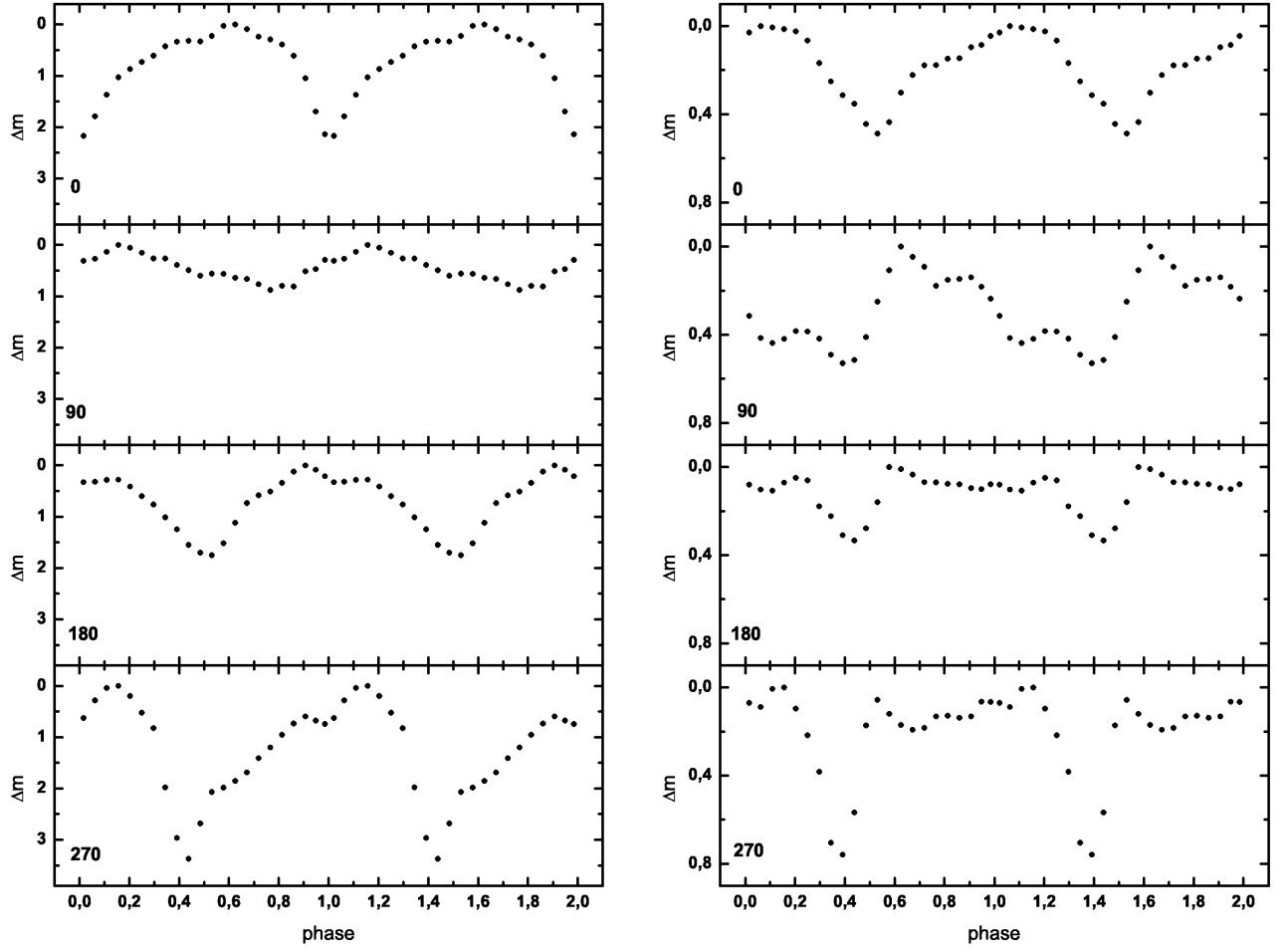


Figure 5: Same as Fig. 3 for model 3 ($e = 0.5, q = 0.03$); (b) the binary orbit is inclined at an angle of 10° to the line of sight.

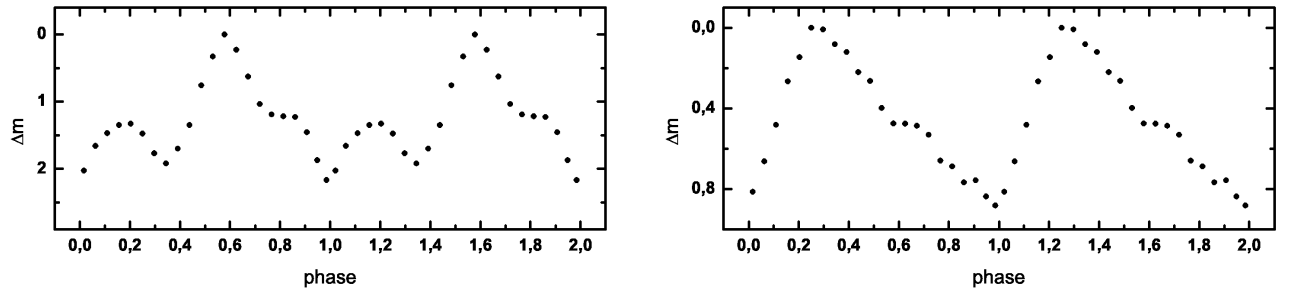


Figure 6: Same as Fig. 3 for model 4 ($e = 0.0, q = 0.01$); (b) the binary orbit is inclined at an angle of 9° to the line of sight.

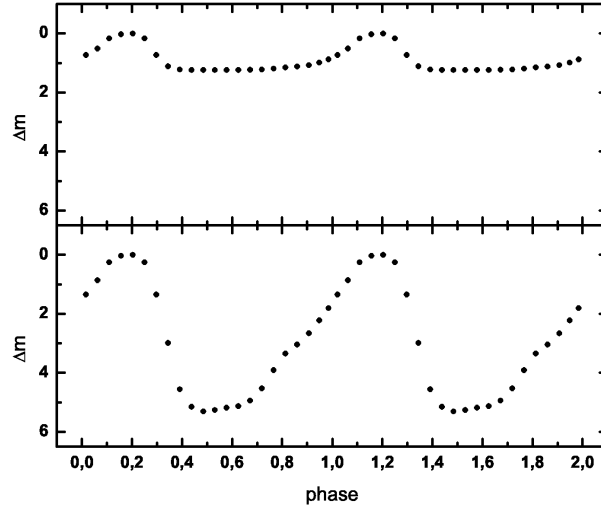


Figure 7: Diagram illustrating the influence of scattered radiation ($I_{sc} = 0.1I_*$) on the behavior of the binary brightness; the light curve in model 1 (a) with and (b) without scattered light.

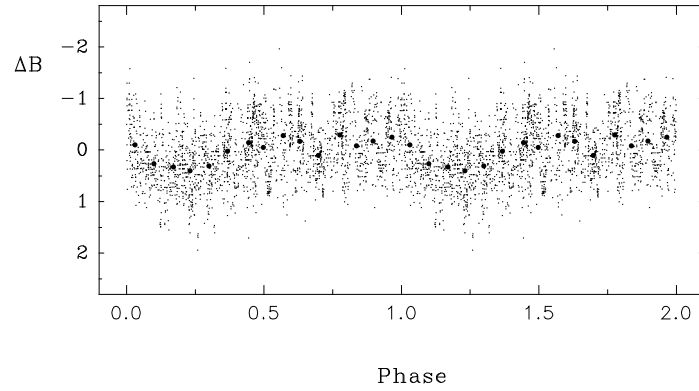


Figure 8: B -band light curve of CO Ori folded with a period of 12.4 yr based on data from Rostopchina et al. (2007).